Vertical segregation in granular mass flows: A shear cell study

B. Cagnoli and M. Manga

Department of Earth and Planetary Science, University of California, Berkeley, California, USA

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[1] Non-fluidised, dry granular mass flows are obtained with rock fragments located on a rough rotating disk. In these flows that develop a quasi-rigid upper layer and a basal layer of colliding particles, dense clasts sink whereas light ones rise when surrounded by particles with intermediate density. Our experiments demonstrate that the presence of a quasi-rigid upper layer in granular mass flows does not prevent vertical segregation and that the formation of coarse-tail grading in pyroclastic flows does not require fluidising gases. High-speed videos reveal that vertical segregation in granular mass flow of rock fragments is generated by inertia differences between segregating clasts and matrix when they are both pushed upward by collisions with the basal layer. Coarse-tail grading occurs because the average segregation velocity of smaller clasts is smaller than that of larger clasts. **Citation:** Cagnoli, B., and M. Manga (2005), Vertical segregation in granular mass flows: A shear cell study, *Geophys. Res. Lett.*, *32*, L10402, doi:10.1029/2005GL023165.

1. Introduction

[2] Although granular flows are extensively studied, their mechanics is sufficiently complex that much remains to be understood [*Duran*, 2000]. In a previous experimental study [*Cagnoli and Manga*, 2004], we found that at the base of rapidly flowing masses of rock fragments travelling within channels, friction does not depend on the shear strain rate as a consequence of the formation of a quasi-rigid upper layer above a relatively thin basal layer of colliding particles. This result is consistent with granular mass flow models of rock avalanches and high-concentration, non-turbulent pyroclastic flows where basal friction behaves according to Coulomb's law [*Iverson and Vallance*, 2001; *Iverson et al.*, 2004; *Sheridan et al.*, 2005].

[3] However, if a granular mass flow model of pyroclastic flows is correct, it has to be compatible with the generation of features that are commonly observed in pyroclastic flow deposits. For example, these deposits can present simultaneously (or separately) a reverse coarse-tail grading of light clasts and a normal coarse-tail grading of dense clasts (Figure 1). With coarse-tail grading we refer to grading affecting only the coarse part of the grain-size distribution of a deposit where matrix particles remain homogeneously distributed [*Cas and Wright*, 1987]. But, how can such particle segregation occur in a quasi-rigid layer? Our experiments allow a detailed understanding of the segregation mechanism in granular mass flows of rock fragments.

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2. Experimental Set-Up

[4] We study the effect of size and density on the vertical segregation of clasts that are completely surrounded by different particles (matrix). Our granular flows are dry and non-fluidised. We compare two sets of experiments using, as matrix, 300 g of 11-mm-sieve-diameter pumice fragments (pumice density 0.5 g/cm^3) and 200 g of 6-mm-diameter glass beads (glass density 2.5 g/cm^3) respectively. With pumice fragments we use, as low-density clasts, two styrofoam cuboids (density 0.05 g/cm^3; edges 15 and 25 mm respectively) and, as high-density clasts, two alumina cuboids (density 2.8 g/cm^3; edges 15 and 25 mm respectively). With glass beads we use, as low-density clasts, two plastic balls (density 1.4 g/cm^3; diameters 6 and 12 mm respectively) and, as high-density clasts, two steel balls (density 8.4 g/cm^3; diameters 6 and 12 mm respectively).

[5] Two sets of ancillary experiments are also carried out with the 6 mm glass beads (2.5 g/cm^3) as matrix. The first is obtained using, as low-density clast, a 25-mm-diameter plastic ball (density 1.4 g/cm^3) surrounded by 800 g of beads. The second is obtained with 200 g of beads and, as larger clast with similar density (2.8 g/cm^3), a 13-mm-diameter glass ball.

[6] In all experiments, we use the shear cell used by *Cagnoli and Manga* [2004], where particles are positioned on a rough rotating disk between two vertical and coaxial glass cylinders (Figure 2). The gap between the two cylinders is ~3 cm in the experiments with pumice (and the 25 mm plastic ball) and ~1.5 cm with glass beads. The smaller gap is obtained by substituting the inner glass cylinder with a larger aluminum one. The tangential speeds of the disk edge are ~2.5 m/sec with glass beads and ~3.3 m/sec with pumice fragments. Because here we consider resultant forces and velocities that are vertical, a distinction between a laboratory reference frame attached to the container and a reference frame attached to the disk is unnecessary.

[7] Clasts with density smaller than that of matrix particles start experiments in contact with disk at the base of the bed, whereas clasts with larger density start experiments from bed top. However, experiments with light and dense clasts in opposite initial positions are also carried out. Each experiment is repeated four times to assess its reproducibility. Our flows are studied using a high-speed video camera at 500 (flows of beads) and 1000 (pumice flows) frames per second.

3. Direction and Velocity of Segregation: Results

[8] Styrofoam cuboids and plastic balls always rise toward the flow top when they start from the bottom (Figures 1 and 3), whereas alumina cuboids and steel balls always sink to the bottom when they start from the top (Figures 2 and 3). These directions of segregation are confirmed by experiments where styrofoam cuboids and

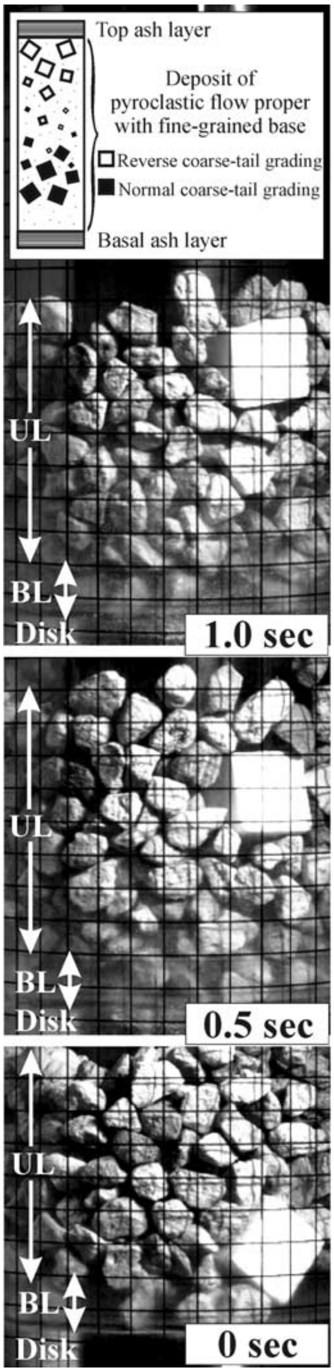

Figure 1. Sequence of frames showing rising styrofoam cuboid in pumice matrix. Values in seconds refer to time elapsed from lower frame. UL and BL stand for upper and basal layer respectively. Inset illustrates coarse-tail grading.

plastic balls that start from the top do not enter the flows and alumina cuboids and steel balls that start from the bottom never reach the top. Also the 25 mm plastic ball segregates upward (Figure 3) whereas the 13 mm glass ball moves toward the flow centre irrespective of its initial vertical position (Figure 4).

[9] The average vertical segregation velocity of larger cuboids and larger balls is larger than that of smaller cuboids and smaller balls respectively. For example in the main sets of experiments, larger clasts are on average ~2 times faster than smaller ones.

4. Segregation Mechanisms: Results and Discussion

[10] The high-speed movies reveal that flows of glass beads and flows of rock fragments have different internal structures even if, in both cases, light clasts rise and dense

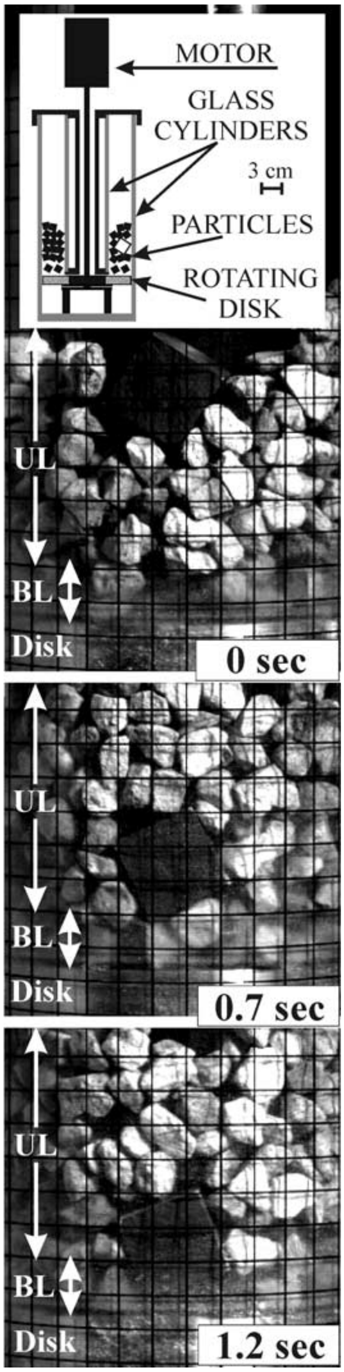

Figure 2. Sequence of frames showing sinking alumina cuboid in pumice matrix. Values in seconds refer to time elapsed from upper frame. UL and BL stand for upper and basal layer respectively. Inset illustrates experimental apparatus.

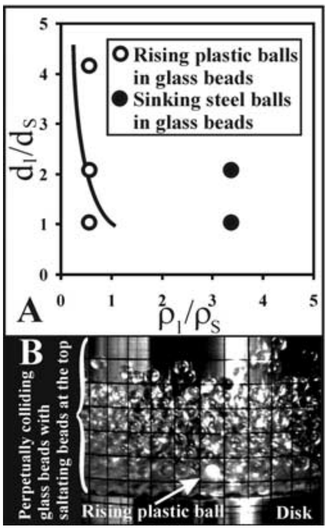

Figure 3. (a) Diameter versus density ratios between segregated balls and matrix beads with plot of equation (2). (b) Example of flow of glass beads.

clasts sink. Flows of rock fragments present a quasi-rigid upper layer and a basal layer of colliding particles [*Cagnoli and Manga*, 2004], whereas glass beads are much more agitated throughout the entire flow thickness (because of their large value of the coefficient of restitution) and present, beside a particularly agitated basal layer, a top zone of saltating beads (Figure 3). These saltating beads do not correspond to the overriding ash-clouds that accompany pyroclastic flows, which are, instead, turbulent suspensions of ash. We expect pyroclastic flows to have an internal structure similar to that of our rock flows and we believe that glass beads should not be used to simulate natural gravity currents.

4.1. Glass Beads

[11] Glass beads impact perpetually a segregating ball's surface. Thus, in any time interval Δt, the total force $\mathbf{S}$ acting on the segregating ball is the sum of its weight and the resultant $\mathbf{C}$ of collisions with glass beads:

$$\mathbf{S} = V\rho\mathbf{g} + \mathbf{C}, \tag{1}$$

where V and ρ are volume and density of the segregating ball and $\mathbf{g}$ is the acceleration of gravity (here, for simplicity, we neglect friction exerted by the apparatus wall). $\mathbf{C}$ is the vector sum of the collisional forces whose individual average magnitudes are equal to $\Delta p_i/\Delta t$, where Δp_i is the momentum change of the *ith* glass bead. The high-speed movies reveal that these collisions are stronger (with larger Δp_i) on the lower surface of a segregating ball than on its upper surface (because the average magnitude of the vertical component of velocity of the glass beads increases downward within the flow due to the interaction with the disk) so that $\mathbf{C}$, in general, has a relatively large vertical component that points upward. It is then the imbalance between weight and $\mathbf{C}$ that determines the direction of segregation. For example, the 13 mm glass ball moves toward the flow centre (Figure 4) seeking the balance of these forces. With glass beads, ρ controls the direction of segregation according to equation (1). This segregation mechanism is similar to that simulated by *Mitani et al.* [2004]. We expect that the difference in magnitude between collisional forces on the upper and lower surfaces of a segregating ball decreases when its diameter decreases so that $\mathbf{C}$ (because of the beads' velocity fluctuations) more easily switches direction (including horizontal) and, consequently, the average vertical segregation velocity decreases.

[12] For comparison, we plot in Figure 3 the following crossover criterion between Brazil-nut effect and reverse Brazil-nut effect obtained in particle mixtures that are shaken vertically [*Breu et al.*, 2003]:

$$d_l/d_s \approx (\rho_l/\rho_s)^{-1}, \tag{2}$$

where d and ρ are diameter and density and l and s refer to segregating and matrix particles respectively. Figure 3 shows that equation (2) (that descends from a model of granular material based on the kinetic theory of gases) does not predict the direction of segregation of our larger plastic ball because rising clasts should plot on the left of the curve.

4.2. Rock Fragments

[13] In granular mass flows of rock fragments, the forces acting on a segregating clast are its weight, particles' friction and the resultant of collisions. Whenever a clast of any density enters the basal layer, it is pushed upward. However, with rock fragments, larger values of the coefficient of internal friction and larger collisional energy losses make the upper layer a relatively more rigid body. This prevents the frenetic perpetual collisions between matrix particles and segregating clast that are seen, on the contrary, with glass beads (for this reason equation (1) is not valid with rock fragments). In quasi-rigid upper layers, segregating clasts find their way up or down when the upper layer briefly expands and the matrix particles' separation temporarily increases such as during the ascent of the oscillating upper layer after its collisions with the basal layer. When the quasi-rigid upper layer does not expand, dense and light clasts are transported without changing vertical position and are supported by particles' friction. Absence of vertical grading is common in pyroclastic flow deposits as well [*Cas and Wright*, 1987].

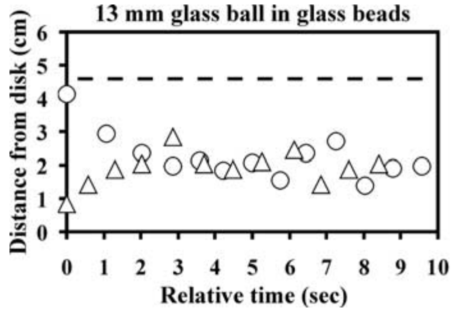

Figure 4. Vertical positions versus time of the center of mass of the 13 mm glass ball that starts experiments at different distances from disk. Dashed line suggests approximate position of flow top below saltating beads.

[14] In granular mass flows of rock fragments, when the oscillating upper layer is pushed upward by collisions that exert forces, on average, with similar magnitude, particles with larger mass have more inertia and tend to be overtaken by lighter ones in their common upward movement. This is true for matrix particles with respect to lighter segregating clasts and it is true for denser segregating clasts with respect to matrix particles. Backtracking is then prevented by matrix filling the segregating fragment's previous position. This ultimately results into the rise of light clasts and sinking of dense ones. Even if, in our apparatus, the segregating effect of inertia may be enhanced by friction exerted by the container glass wall (that is proportional to the particle mass because of the centripetal force), we suggest that, in nature, inertia alone can produce vertical segregation in oscillating upper layers when their particles move upward and separate. This segregation does not occur when oscillating upper layers move downward because particle separation decreases (due to the containing effect of the disk or ground) and they are not pushed downward by collision with an upper boundary.

[15] The segregation effect of inertia is controlled by mass differences between segregating clasts and clusters of surrounding matrix particles (instead of that of a single matrix particle) because of their relatively large value of the coefficient of internal friction. For this reason, also in granular mass flows of rock fragments, density affects segregation. In particular, because the mass difference between equal size volumes of different density increases when the volume increases (for example, the mass difference between a segregating clast and an equal volume of matrix increases when this volume increases), larger clasts segregate faster than smaller ones. Different average segregation velocities produce, in the same interval of time, coarse-tail grading. Thus, in ignimbrites, large pumice clasts with density smaller than that of pumice matrix migrate upward. We expect segregation velocity to vary with vertical position and, given enough time, a concentration of the segregating clasts at the flow top and bottom. This concentration is visible in some pyroclastic flow deposits [*Cas and Wright*, 1987].

[16] It is important to understand that, in different systems, there can be significantly different segregation mechanisms [*Rosato et al.*, 1987; *Ottino and Khakhar*, 2000]. For example, the segregation mechanism in our flows of rocks is different from kinetic sieving, which is, however, possible in pyroclastic flows as well. Our segregation mechanism produces grading of clasts that are completely surrounded by different fragments. Kinetic sieving, on the other hand, consists of the fact that, when shaken, particularly small fragments will fall unavoidably in the gaps between larger particles.

[17] We should also note that the dispersive pressure suggested by *Bagnold* [1954] (that is proportional to the square of the particle diameter) explains only the upward drift of larger grains, whereas our mechanism explains also their concomitant downward motion. Finally, we wonder whether other clast features beside size and density (such as fragment shape and surface roughness) can affect segregation [*Vallance and Savage*, 2000].

5. Conclusions

[18] Our experiments confirm that in granular mass flows of rock fragments, an oscillating quasi-rigid upper layer is rigid enough for Coulomb friction law to be valid at its base [*Cagnoli and Manga*, 2004], but it does not prevent vertical segregation of clasts when it expands because of collisions and vibrations. Thus, a granular mass flow model of pyroclastic flows with a quasi-rigid upper layer and a basal layer of colliding particles [*Cagnoli and Manga*, 2004] is consistent with a feature that is commonly observed in pyroclastic flow deposits: the reverse coarse-tail grading of light clasts and the normal coarse-tail grading of dense clasts. Our experiments suggest that vertical segregation in natural granular mass flow is generated by inertia differences between segregating clasts and matrix when they are both pushed upward by collisions with the basal layer. Coarse-tail grading is the result of the fact that the average segregation velocity increases when clast size increases. We conclude that the formation of coarse-tail grading does not require fluidising fluids.

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B. Cagnoli and M. Manga, Department of Earth and Planetary Science, University of California, 307 McCone Hall, Berkeley, CA 94720, USA. (cagnoli@seismo.berkeley.edu)